*Igneous and metamorphic rocks of the western portion of*

# Joshua Tree National Monument

**Riverside and San Bernardino Counties**
**California**



**CALIFORNIA DIVISION OF MINES**

SPECIAL REPORT 68

The cover: Towering piles of granite (weathered and jointed White Tank quartz monzonite) in Joshua Tree National Monument. *Photo courtesy National Park Service.*

# IGNEOUS AND METAMORPHIC ROCKS OF THE WESTERN PORTION OF JOSHUA TREE NATIONAL MONUMENT,

## RIVERSIDE AND SAN BERNARDINO COUNTIES, CALIFORNIA

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## *Preface*

This paper is published essentially as prepared by Dr. John J. W. Rogers as a contribution to the basic geology and petrology of the western portion of Joshua Tree National Monument. As the study was not concerned with economic mineral deposits, no mention of these is made. The Division of Mines has, however, a report under preparation on the mines and mineral deposits of Riverside County which includes most of the area of this report and which will include discussion of possible mineralization in the district. The mineral deposits in the remaining and northern part of San Bernardino County already have been described in the *California Journal of Mines and Geology*, volume 49, numbers 1 and 2, January-April 1953.

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## ABSTRACT

The western portion of Joshua Tree National Monument consists primarily of the Pinto gneiss, a metasedimentary rock unit of probable Precambrian age. The gneiss is well foliated, generally with a steep dip and north to northwesterly trend, and is composed of quartz, oligoclase, biotite, and a few minor minerals such as potash feldspar and muscovite. The gneiss is injected, particularly in the area south of Twenty-nine Palms, by a complex series of intrusive rocks. The oldest of these intrusive rocks is the Gold Park gabbro-diorite, which occurs in a few small, scattered bodies. Next in age is the Palms quartz monzonite, which has been subdivided into three units on the basis of slight compositional and textural differences. Along some of the contacts between Palms quartz monzonite and gneiss is a monzonitic porphyry characterized by large (up to 6 inch) crystals of potash feldspar. The porphyry appears to have formed by reaction between the gneissic wall rock and the invading Palms quartz monzonite. From the gneiss, through the porphyry, and into the quartz monzonite there is a steady increase in the amount of potash feldspar and in the albite/anorthite ratio of the plagioclase and a decrease in the amount of mafic minerals.

The White Tank quartz monzonite (probably Jurassic) is the youngest of the major intrusive rocks and forms large, roughly circular, plutons around which the gneissic foliation is concordant. The four plutons mapped differ in mineralogy and texture. The largest one (in Queen Valley and vicinity) shows a vertical lithologic variation that is attributable to gravitative settling in a magma. Igneous activity following the White Tank quartz monzonite has formed a small body of granodiorite, minor dike rocks, and basaltic plugs.

The area is cut by three major east-west faults, the movement on which cannot definitely be determined. In many places faults occur along abrupt mountain fronts facing alluviated valleys. Valleys are also formed by differential erosion of the readily disintegrated White Tank quartz monzonite against Pinto gneiss and Palms quartz monzonite which are relatively resistant. Pediments are extensively developed along the margins of valleys in the White Tank quartz monzonite.

# IGNEOUS AND METAMORPHIC ROCKS OF THE WESTERN PORTION OF JOSHUA TREE NATIONAL MONUMENT

## RIVERSIDE AND SAN BERNARDINO COUNTIES, CALIFORNIA *

By JOHN J. W. ROGERS

### INTRODUCTION

*Purpose.* From June, 1953 to August, 1954, the writer carried on a study of the textural features in the igneous rocks exposed in Joshua Tree National Monument south of Twentynine Palms, California. In the course of this investigation, observations were made on the general geologic nature, age relations, structural features, and mode of formation of the crystalline rocks throughout the western part of the Monument. The object of the present paper is to summarize the field and petrographic information obtained in this study without burdening the reader with extensive textural detail.

*Location.* The location of Joshua Tree National Monument and the area dealt with in the present work are shown in figure 1. The index map also distinguishes between the portion of the area studied in detail and the portion covered only in reconnaissance fashion.

Most of the area shown in figure 1 lies in the Little San Bernardino Mountains, a northwesterly trending range which makes up the northeastern border of the Coachella Valley. Extending east from the Little San Bernardino Mountains, and partly included in the map area, are the Pinto and Hexie Mountains. The northern edge of the area mapped is marked by the Pinto Mountain fault (Hill, 1928), an east-west fault cropping out about a quarter of a mile north of the mountainous region.

*Physiography.* Joshua Tree National Monument occupies part of a broad mountainous belt which trends east-west across southern California. Much of the Monument has an elevation of 4,000 feet or more, and both on the north and the south the mountains exhibit steep scarps rising from the surfaces on either side of the area.

Within the western portion of the Monument are a number of separate mountain ranges and intervening valleys which are shown on the geologic map. The Little San Bernardino Mountains comprise the southwestern portion of the map area and are underlain largely by the Pinto gneiss or its migmatized derivatives (as are most of the other mountain ranges in the area). The southern face of the range is probably a fault scarp. The range extends in a west-northwesterly direction and thus makes an angle of approximately 45 degrees with the gneissic foliation in the area. The Lost Horse Mountains extend north from the Little San Bernardino Mountains and may be the topographic expression of a gneissic screen between two bodies of the White Tank quartz monzonite. The Hexie Mountains consist of a mass of Pinto gneiss which extends east from the Little San Bernardino Mountains and whose topographic expression may be partly the result of movement along the Eagle Mountain fault at the southern edge of the range. As the name suggests, the Pinto Mountains also consist largely of the Pinto gneiss, which strikes in the regional north to northwesterly direction and dips steeply. On the north, the range is bordered (at least in part) by the Pinto Mountain fault, and the southern face of the mountains may also represent a fault scarp separating the range from the Pinto Basin. South of Twentynine Palms a mountainous mass extends to Queen Mountain and is underlain largely by the Palms quartz monzonite. Both lithologic and topographic evidence suggest that the southern face of Queen Mountain is a fault scarp.

The valleys separating the mountain ranges mentioned above may be subdivided into two categories. The first type includes Pleasant Valley and the Pinto Basin (just to the east of the map area), both of which are underlain by an unmeasured thickness of alluvium. Pleasant Valley is almost certainly bordered on the north by the Eagle Mountain fault, and the Pinto Basin may also be a topographic unit as a result of faults along one or more sides. Not all valleys, however, may be attributed to faulting or are underlain by large quantities of allu-

* Based upon a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Division of Geological Sciences, California Institute of Technology, Pasadena, California; manuscript submitted to the Division of Mines for publication February 1955. Publications of the Division of the Geological Sciences, California Institute of Technology, Pasadena, California—Contribution No. 832.

Photo 1. View east across Lost Horse Valley toward the Lost Horse Mountains. On Ryan Mountain (in background) dark Pinto gneiss is intruded by light White Tank quartz monzonite. In middleground typical outcrop of jointed White Tank quartz monzonite in Lost Horse Valley. Area of Ryan Campground in foreground. *Photo courtesy National Park Service.*

Photo 2. View south across Indian Cove Campground. Rounded outcrops in foreground are typical exposures of jointed White Tank quartz monzonite. *Photo courtesy National Park Service.*

vium, and a second type of valley is formed on broad outcrops of the White Tank quartz monzonite and results from the fact that the jointed, disintegrated quartz monzonite shows far less resistance to erosion than do any of the other rocks in the area. Intrusive contacts between gneiss and remnants of the quartz monzonite high on the slopes of the Pinto, Hexie, and Lost Horse Mountains indicate that the relief is not caused by faulting along the contact between the two rocks. Valleys in the quartz monzonite (such as Queen and Lost Horse Valleys) characteristically contain numerous monoliths of the rock separated by a surface of loose sand derived from the quartz monzonite. Each monolith is cut into many large joint blocks, and the resulting grotesque appearance has led to such descriptive names as "Wonderland of Rocks" and "Jumbo Rocks." The western part of Lost Horse Valley is underlain by Unit C of the Palms quartz monzonite rather than by the White Tank quartz monzonite, but the two rocks are texturally and compositionally so similar that they exhibit almost identical topographic features.

It is interesting to note that the north-south drainage divide for the Monument extends over a broad and nearly flat area of the White Tank quartz monzonite just south of Queen Valley rather than along the crests of the ranges north or south of this outcrop.

Mountain fronts, whether formed by faulting or differential erosion, are universally steep. Slopes of thirty degrees are common in many places. On the south face of Queen Mountain, over-steepening has proceeded to such an extent that landsliding has occurred, and small talus slopes are present in other parts of the area. Canyons cut into the mountains are almost invariably "V-shaped" and steep-sided.

South of the Pinto Mountain fault a number of pediments have been developed at the base of the steep mountain front near the northern edge of the Monument. The most extensive cutting has occurred on the granitic rocks, namely the White Tank quartz monzonite and Unit C of the Palms quartz monzonite. The pediments are marked by small remnant knobs of quartz monzonite and are characteristically covered by a veneer of gravel several feet thick.

At the mouths of canyons along the southern face of the Little San Bernardino Mountains, small fans have formed. Many of these fans have been incised, apparently by the same streams that formed them, and it is not certain whether the present streams are eroding or

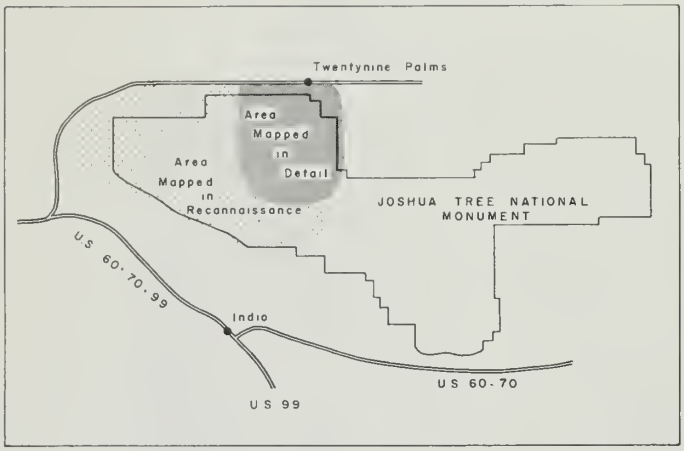



Figure 1. Index map.

constructing the fans. Also undetermined is the extent to which the slopes south of the Little San Bernardino Mountains and away from the major canyons have been formed by deposition of fans. Fans also have been built, in some places, next to the mountain front on the north side of the Monument.

Within the Monument the change from valley floor to mountain face is characteristically abrupt, and small fans or pediments have developed locally. Small pediments cut on White Tank quartz monzonite bedrock may be seen along the sides of many of the gneissic mountain ranges. Streams on these pediment surfaces have cut into bedrock at depths of only a few feet below a veneer of gravel.

One interesting feature shown at many places in the Monument is the difference in rates of erosion exhibited by the relatively coarse-grained White Tank quartz monzonite and the fine-grained aplite dikes that intrude it. The quartz monzonite is far more disintegrated than the aplite and almost invariably is eroded more rapidly than the aplite. Dikes commonly project beyond the surface of the quartz monzonite on all outcrops where both rocks are present. The ability of fine-grained rocks to resist disintegration and erosion is also demonstrated by the fact that the aphanitic olivine basalt which comprises Malapai Hill stands as a resistant knob above the quartz monzonite which it intrudes.

Photo 3. Wonderland of Rocks; view northwest from Lost Horse Mountain. Weird surface formed by weathering of White Tank and Palms quartz monzonites. *Photo courtesy National Park Service.*

Natural arches occur at several places in outcrops of the White Tank quartz monzonite. Commonly the arches appear to follow curved joint surfaces, below which the disintegrated rock has been removed.

*Procedure.* Mapping in the area south of Twentynine palms, (in the vicinity of the White Tank quartz monzonite), was done on aerial photographs obtained from the U. S. Air Force, photographic Records and Services Division, which covered part of the region designated by the Air Force as the Pine Knot Area. Mapping in the remainder of the western part of the Monument was done on maps compiled by the Engineering Branch of the National Park Service. The map published with this paper is compiled largely from the writer's own work, but is also adapted partly from the work of Miller (1938) and Maclellan (1936).

*Acknowledgments.* Most of the work discussed in this paper was done as a Ph.D thesis project at the California Institute of Technology, and the writer would like to thank the staff of the Geology Department for their much-needed assistance. Especial thanks must be given to Dr. Ian Campbell, who supervised the project. The writer is also extremely grateful to the staff of the National Park Service in Joshua Tree National Monument for their permission to work in the Monument and for their invaluable assistance in the field.

## PREVIOUS WORK

Geologic studies in the area covered by the present paper were previously made by W. J. Miller (1938). Miller delineated the formations exposed in the portion of the Monument south of Twentynine Palms and named all of the major rock units in the area. A summary of the crystalline rocks of southern California is given by Miller (1946).

Harder (1912) studied the iron ores of the Eagle Mountains, about 20 miles southeast of the area covered in the present report. Evidence presented in his paper indicated that the dominant events in the evolution of the crystalline rocks in the Eagle Mountains were: first, sedimentation; second, intrusion of porphyritic granite; third, dynamic metamorphism of both granite and sediments; and fourth, intrusion of quartz monzonite.

Vaughan (1922) reported principally on the San Bernardino Mountains, about 25 miles west of the western edge of Joshua Tree National Monument. The major events in the development of the crystalline rocks of this area were: first, the formation of Precambrian schists and granites; second, intrusion of a granitic rock best dated as post-Carboniferous; and third, the intrusion of the Cactus granite of probable Jurassic age.

Maclellan (1936) has studied an area largely south of Joshua Tree National Monument in the Little San Bernardino Mountains. The geologic history of the area is: first, metamorphism of sediments to form the Berdoo series; second, greater metamorphism and migmatization of part of the Berdoo series to form the Thermal Canyon series; and third, intrusion of the Fargo granite. The Berdoo series is probably correlative with the Pinto gneiss discussed in this report, but although the Pinto gneiss is locally migmatized, the area studied by the writer apparently does not contain any large, mappable bodies of rock similar to those delineated as the Thermal Canyon series. Descriptions of the Fargo granite indicate that it is probably correlative with the White Tank quartz monzonite described in this report.

Although the writer has concluded that the Pinto gneiss is the oldest formation in the area and consists almost entirely of metasediments or metavolcanics, Miller (1938) showed evidence that much of the gneiss was derived from plutonic igneous and meta-igneous material. With this exception, the chronologies indicated by Miller and the writer for the formation of the crystalline rocks in the area appear to be identical. Essentially the sequence consists of an early period of igneous and metamorphic activity followed by the intrusion of the White Tank quartz monzonite.

Thus, the general history of the crystalline rocks in the area around Joshua Tree National Monument is one of relatively recent (probably Jurassic) intrusion of quartz monzonite into an igneous-metamorphic complex. There is some indication of a period of igneous activity between the formation of the igneous-metamorphic complex and the intrusion of the quartz monzonite, but there is no evidence as to its exact age. Although the writer is not convinced that any of the periods of magmatic intrusion have been followed by large-scale metamorphism, it must be admitted that several investigators have reported the metamorphism of plutonic igneous rocks as part of the history of the region.

A more detailed map of the area just south of Twentynine Palms and a very brief summary of the geology of the area has already been published by the writer (Rogers, 1954).

## LITHOLOGY

### Pinto Gneiss

The Pinto gneiss was first named by Miller (1938). Although his discussion was restricted to an area near Twentynine Palms, the writer believes that the Pinto gneiss includes similar and apparently correlatable rocks throughout a large area in and around the western part of Joshua Tree National Monument. Some of the possible correlatives are the Berdoo series (described by Maclellan, 1936) and the Chuckwalla complex (described by Miller, 1944).

The Pinto gneiss is probably the oldest formation in the western part of the Monument. All of the igneous rocks appear to intrude the gneiss, although the age relations of some are not certain. The absolute age of the gneiss, however, is unknown.

*Composition and Texture.* The Pinto gneiss is a middle rank metamorphic rock characterized by plagioclase (albite to andesine), biotite, and quartz. Potash feldspar and muscovite occur in some facies, and amphibole, concentrated into thin bands of amphibolite, is also present. Rare grains of reddish brown garnet are scattered through the rock. The grain size of most minerals ranges from one-eighth to one millimeter, and some sections contain alternating one- to two-millimeter bands (parallel to the foliation) of different grain sizes. The foliation bands average from one-half to three millimeters wide and maintain a constant thickness within a given specimen. Portions of the rock mapped as gneiss up to a mile or so in diameter (and apparently randomly distributed) are almost completely devoid of foliation. Photo 4 shows a typical section of the gneiss.

Photo 4. Photomicrograph of Pinto gneiss. Quartz, the most abundant mineral, forms coarse irregular grains. Biotite forms flakes parallel to the foliation. Slightly below and left of center is an aggregate of fine grained, felty, muscovite. Crossed nicols, X25.

About 90 percent of the Pinto gneiss is dark colored and characterized by the presence of biotite. An average composition is:

| Mineral | Percent |
|---|---|
| Quartz | 50 |
| Potash feldspar | 5 |
| Plagioclase | 20 |
| Biotite | 15 |
| Muscovite | 10 |
| Accessory | 0.2 |

Plagioclase ranges from albite to andesine in different specimens and averages about $An_{20}$. Plagioclase is generally twinned, invariably unzoned, and forms the largest grains in the gneiss (up to two millimeters). Quartz commonly forms layers several millimeters wide and devoid of all other minerals; the borders between quartz grains are highly sutured. Biotite is pleochroic from yellow to dark brown and occurs in bands approximately one millimeter wide between bands of quartz and feldspar. Muscovite forms masses, several millimeters in diameter, of tiny, interlocking crystals; possibly these masses are pseudomorphs of some other mineral. Potash feldspar is lacking in many specimens; where it does occur, it forms small, irregular grains. The most common accessory mineral is magnetite, but rutile is present in some specimens in which the biotite appears to have been chloritized. All grains except the accessory minerals are anhedral, and most are morphologically and/or optically oriented parallel to the foliation.

Almost all of the Pinto gneiss not included in the biotitic facies consists of a light-tan, well-foliated, feldspathic, rock with the following average modal composition:

| Mineral | Percent |
|---|---|
| Quartz | 40 |
| Potash feldspar | 25 |
| Plagioclase | 30 |
| Biotite | 4 |
| Muscovite | 1 |
| Accessory | 0.2 |

The average grain size in this light colored gneiss is slightly smaller than the grain size of the biotitic gneiss, and grain orientation is not as well developed as in the biotitic rock. The average composition of the plagioclase is $An_{20}$, and most of the grains are twinned and unzoned. Biotite is pleochroic from yellow to dark brown and forms very irregular flakes. The most common accessory mineral is magnetite. Except for the accessory minerals, all grains are anhedral.

In addition to the biotitic and feldspathic types of gneiss, a few thin (less than ten feet wide) bands of black amphibolite are scattered throughout the Pinto gneiss. One sample contains an estimated 65 percent of yellow to greenish-blue hornblende prisms, 30 percent untwinned, anhedral plagioclase ($An_{50}$), 5 percent biotite, and rare quartz, magnetite, and apatite. The average grain size is one-fourth millimeter.

The non-foliated (granitoid) portions of the rock mapped as Pinto gneiss appear to be randomly distributed throughout the formation. In general, these portions contain slightly more potash feldspar and less quartz than the rest of the gneiss but otherwise are mineralogically identical with either the biotitic or feldspathic facies of the gneiss. Foliation, where present at all, is indicated by alignment of biotite. The average grain size is 0.5 millimeter, and all grains are anhedral. An excellent example of non-foliated rock occurs south of Quail Spring.

One-half mile east of Stirrup Tank is a type of foliated feldspathic gneiss which contains only 25 to 30 percent quartz and, thus, has a composition similar to that of the non-foliated portion of the formation. Such combinations of low quartz content and well-developed foliation, however, are very uncommon.

*Structure.* Throughout the area the gneissic foliation shows a general north to northwesterly strike and nearly vertical dip. Both on a broad scale and in detail, however, the foliation trends parallel to the contact with

the White Tank quartz monzonite in the Pinto, Hexie, and Lost Horse Mountains. Thus, in areas of intrusion of the White Tank quartz monzonite the gneissic foliation is bent away from the regional trend as if warped by the same force which caused the intrusion of the quartz monzonite.

In the Pinto and Hexie Mountains, for distances of up to a mile from the quartz monzonite contact, the gneissic foliation strikes parallel to the contact but shows extreme variation in dip. In fact, the entire gneiss in this region is contorted into nearly vertical, isoclinal folds with a width seldom exceeding 50 feet. The dip of the foliation ranges from vertical through horizontal and back to vertical in the space of a few feet. In the Lost Horse Mountains this intricate folding and variation in dip is not present, and the reason for its presence in one place and absence in another is not known.

Detailed mapping in the Lost Horse Mountains shows the presence of folded structures, although the general trend is north-south. In detail, the foliation parallels the contact with the quartz monzonite, and in the northern part of the mountains there is some indication that a regional foliation making an angle up to 30 or 40 degrees with the contact is warped into parallelism within a foot or so of the contact. In other places, however, gneiss with a regional strike at an angle of approximately 60 degrees to the contact is cut obliquely by the quartz monzonite.

One of the most striking features of the gneiss is the banding shown by the biotitic and feldspathic facies. In the Lost Horse Mountains these two types form layers 100 to 500 feet thick and generally parallel to the foliation. In places there is compositional gradation between these facies, but generally a sample of the gneiss is definitely of one or the other type.

*Origin.* For several reasons the Pinto gneiss is thought to be almost entirely the product of metamorphism of sedimentary or volcanic material. For instance, layers of different composition several hundred feet wide and parallel to the foliation (as in the Lost Horse Mountains) seem most easily explained by metamorphism of a layered sequence. This evidence does not distinguish between metasediments and metavolcanics.

Secondly, the difference in the composition of the plagioclase in different layers indicates formation in a chemically non-homogeneous system. If, as seems possible, this lack of homogeneity represents chemical differences in the original rock, then the parent rock was more likely sedimentary or volcanic than plutonic.

Thirdly, the average quartz content of the gneiss is approximately 50 percent. Such a high percentage suggests a sedimentary rather than an igneous parent rock.

Assuming that the Pinto gneiss formed by middle-rank metamorphism of sedimentary or volcanic rocks, it is difficult to determine the exact nature of the parent rock. The composition indicated by modal analysis of the gneiss (and assuming isochemical metamorphism) is similar to the composition of graywackes * except for a higher potash-soda ratio (K/Na averages 1 to 1.5 in the Pinto gneiss). The total silica content seems too high for normal igneous rocks but may well represent the composition of mixed sedimentary and volcanic material. No relict textures or structures, other than the large-scale layering, have been found which would aid in determining the nature of the parent material. The gneiss of quartz-monzonitic composition east of Stirrup Tank may be a true metamorphosed igneous rock, or it may represent transition into the Palms quartz monzonite or the non-foliated portion of the gneiss.

The mode of formation of the granitoid, non-foliated parts of the formation is not known. They may be related to the emplacement of the Palms quartz monzonite, and some geologists would probably consider them to be the product of magmatic intrusion into the gneiss. On the other hand, they may be recrystallized gneiss lying above areas of magmatic or metasomatic emplacement of quartz monzonite. But in many places there seems to be no spatial relation between the Palms quartz monzonite and the non-foliated portions of the Pinto gneiss. At contacts between the Palms quartz monzonite and the gneiss, the most common effect is the formation of migmatite and other rocks of apparently mixed metamorphic and igneous origin; at only one contact (east of Queen Mountain) is the gneiss pronouncedly recrystallized by the Palms quartz monzonite to rock similar to the large areas of non-foliated material. Thus, although the granitoid portions of the gneiss probably developed at a late stage of, or subsequent to, the metamorphism which produced the gneiss, they apparently are unrelated to the Palms quartz monzonite and may represent a separate phase of plutonic activity.

* As given by Pettijohn (1949), p. 250.

### Gold Park Gabbro-Diorite

The Gold Park gabbro-diorite was first named and described by Miller (1938). The formation occurs in small, isolated outcrops scattered throughout the area investigated.

*Composition and Texture.* The gabbro-diorite is a dark gray, massive, coarse- to fine-grained, inequigranular rock which shows extreme textural and compositional variation. Perhaps the most common variety is characterized by hornblende prisms several millimeters long which poikilitically enclose subhedral laths of plagioclase. Another type of gabbro-diorite is fine-grained and equigranular and consists largely of plagioclase and biotite with approximately 10 percent accessory minerals.

Modal analyses of these two types of gabbro-diorite gave the following results:

| Minerals | Coarse-grained rock with poikilitic hornblende | Fine-grained, equigranular, rock |
|---|---|---|
| Plagioclase | 43.8% | 47.4% |
| Hornblende | 46.7 | 7.3 |
| Biotite | ---- | 28.5 |
| Olivine | 0.2? | 3.8 |
| Chlorite | 3.6 | ---- |
| Augite? | ---- | 0.9? |
| Magnetite | Not separated from other accessories | 6.4 |
| Other accessory | 5.6 | 5.8 |

Plagioclase in both rocks is normally zoned, the range being from labradorite to andesine in the coarse-grained rock and from calcic andesine to calcic oligoclase in the fine-grained rock; some of the oligoclase is antiperthitic. Hornblende in both sections mentioned above is pleochroic from yellow green to greenish blue. Biotite is pleochroic from yellow to dark brown. The identification of

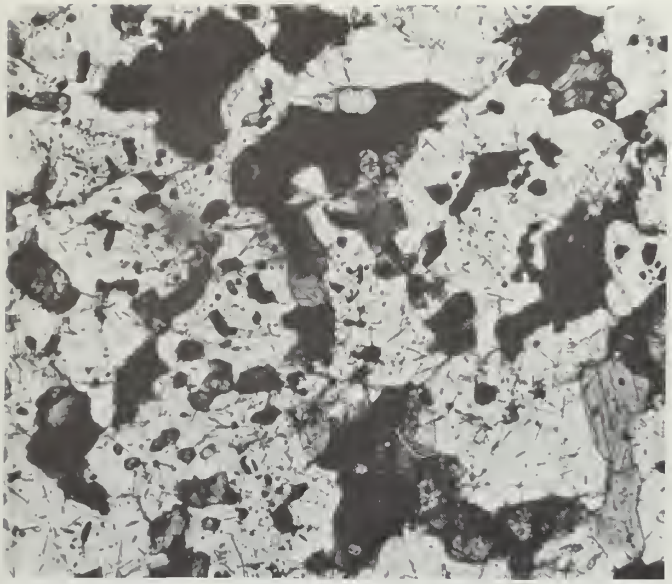


Photo 5. Photamicrograph of Gold Park gabbro-diorite. The majar (white) mineral is plagiaclase. Dark grains are primarily biatite with same magnetite and small grains of olivine. The tiny needles are apatite (?). Plain light, X65.

pyroxene in the equigranular rock is uncertain. The equigranular rock contains up to five percent colorless, low birefringent, tiny needles with hexagonal cross-sections; these needles are tentatively identified as apatite. Alteration products are common only in the coarse-grained gabbro-diorite; plagioclase is intensely sericitized, and hornblende is altered to chlorite and a mineral tentatively identified as sphene. Photo 5 shows a typical section of the fine-grained gabbro-diorite.

*Structure.* No structure has been found in the gabbro-diorite, but the intense weathering of most outcrops makes detection of structure difficult.

*Origin.* Although the Gold Park gabbro-diorite probably formed by crystallization of a melt, some mineralogical details are difficult to explain by such a process. The presence of olivine and hornblende in one sample and the absence or scarcity of pyroxene seems to contradict crystallization according to the standard Bowen reaction series.

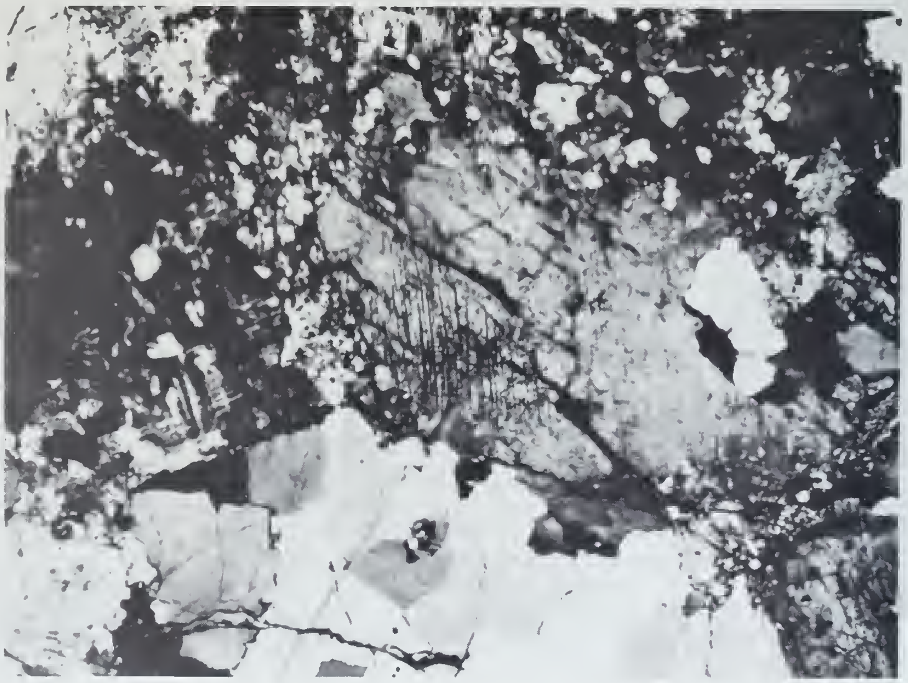
### Palms Quartz Monzonite and Monzonitic Porphyry

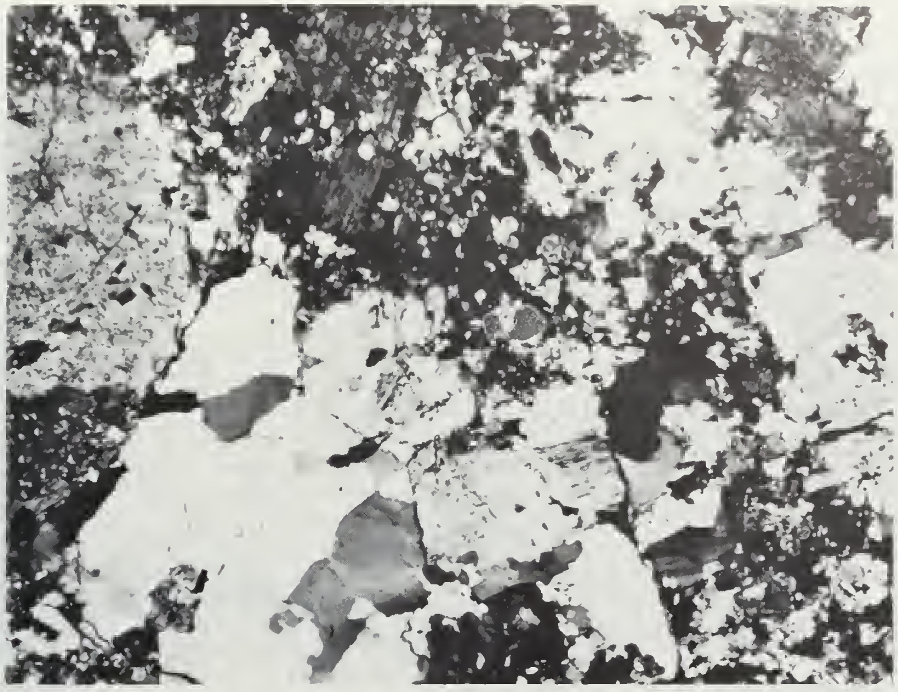
The Palms quartz monzonite crops out in the mountains south of Twentynine Palms, in Queen and Lost Horse Valleys, and in the area west of Lost Horse Valley. South of Twentynine Palms the rock is typically coarse- to medium-grained and inequigranular, but in Queen and Lost Horse Valleys and west of Lost Horse Valley, the rock is finer grained and more equigranular. Miller (1938) described the Palms granite (with typical exposures south of Twentynine Palms).

The monzonitic porphyry (described by Miller, 1938) crops out around the northern periphery of the mountainous area south of Twentynine Palms. For reasons to be discussed later, the porphyry is considered to be intimately related genetically to the quartz monzonite.

The Palms quartz monzonite and monzonitic porphyry are younger than the gneiss, as is shown by dikes of each rock in the gneiss at various places. Contacts between the quartz monzonite and the gabbro-diorite are invariably so gradational that no exact age relations may be stated, although in places the quartz monzonite appears to invade and inject the gabbro-diorite. Dikes of quartz monzonite cut the monzonitic porphyry and vice versa, a further indication of the genetic relation between the two rocks. The absolute age of the Palms quartz monzonite and monzonitic porphyry is unknown.

Photo 6. Photamicrograph of Unit A of Palms quartz monzonite. The majar minerals are quartz (aggregate af coarse grains), a large crystal af plagioclase (center af the picture), and microcline (shawing same grid twinning). All minerals are seriate from the large crystals to the smallest grains shawn here. Crossed nicols, X25.



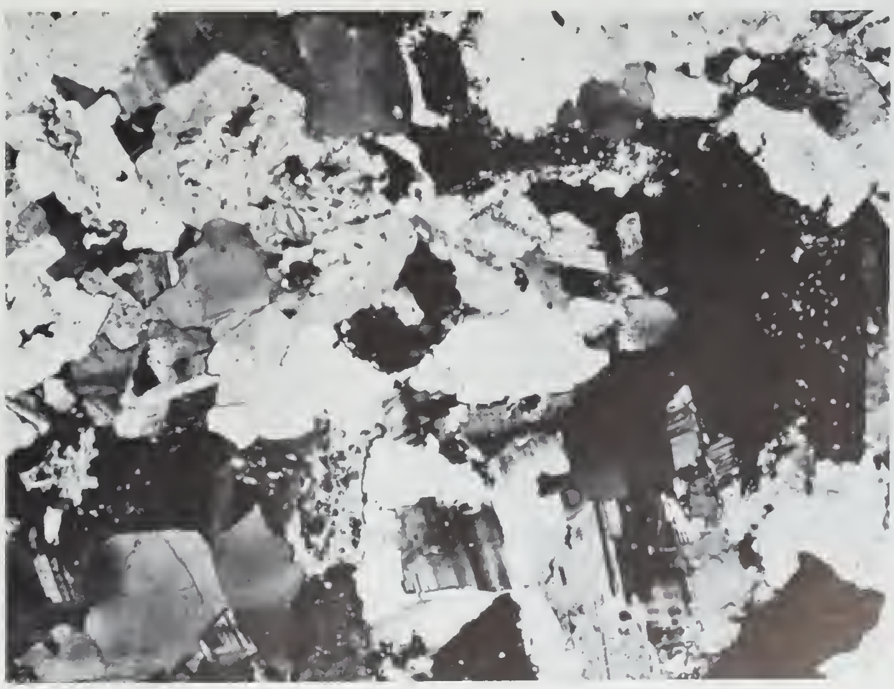


Phota 7. Photomicrograph af Unit B of Palms quartz monzonite. Major minerals are quartz (in aggregates), plagioclase (paarly twinned, altered), and micracline (shawing grid twinning). Crassed nicols, X25.

*Composition and Texture of the Palms Quartz Monzonite.* The Palms quartz monzonite is a gray to brown, coarse- to fine-grained, generally massive rock which may be divided into three types: Unit A (Photo 6), a coarse-grained rock as in the type area near Forty Nine Palms; Unit B (Photo 7), a finer-grained rock in the upper part of the mountains south of Twentynine Palms; and Unit C (Photo 8), a fine-grained rock in Queen and Lost Horse Valleys and the area west of Lost Horse Valley. An average composition of the formation is approximately 30 percent quartz, 30 percent potash feldspar, 40 percent plagioclase (oligoclase), and a few percent biotite and accessory minerals.

Unit A, the rock in Forty Nine Palms Canyon and the mountainous area to the south, is coarse-grained, very inequigranular, generally massive, and ranges from brown to gray. Foliation, caused by alignment of biotite flakes, is present in some places, but no general foliation trends could be found, even over small areas. An average modal analysis of this coarse-grained rock is as follows:

Phata 8. Phatomicragraph af Unit C af Palms quartz manzonite. Majar minerals are quartz (undulant), plagiaclase (well twinned), and micracline (grid twinned). Crassed nicals, X25.



| Mineral | Percent |
|---|---|
| Quartz | 28 |
| Potash feldspar | 25 |
| Plagioclase | 40 |
| Biotite | 5 |
| Hornblende | 0.5 |
| Accessory | 2 |

Quartz forms aggregates of sutured grains. Plagioclase ranges from $An_{30}$ to $An_{15}$, the more calcic grains generally zoned and the more sodic grains twinned. Potash feldspar and plagioclase are typically complexly intergrown, the borders between the two minerals being characterized by islands of each mineral in the other. Biotite is pleochroic from yellow to reddish-brown. Perthite, myrmekite, and fine grained, interstitial albite are common. Common blue-green hornblende is present in a few sections. Magnetite, sphene, apatite, and epidote are present in almost all sections, but zircon and allanite are rare. All of the major minerals are anhedral, and the accessory minerals are generally euhedral.

Dikes of Unit A in either monzonitic porphyry or gneiss are either fine grained and equigranular or contain phenocrysts of plagioclase in a fine-grained groundmass. The best exposure of these dikes is in the monzonitic porphyry east of Indian Cove.

In the higher parts of the mountains around and south of Forty Nine Palms is a facies of quartz monzonite slightly different from Unit A. This facies (Unit B) everywhere lies above Unit A, but the contact between the two rocks is completely gradational and very difficult to locate.

In distinction to the massive Unit A, Unit B is poorly to well foliated. Generally, the foliation is nearly vertical and parallels the northwesterly trend of the Pinto gneiss. Foliation is marked by orientation both of biotite flakes and elongate aggregates of quartz grains. Some parts are apparently massive.

Units A and B are very similar in bulk chemical composition and general textural features. The chief differences between the two rocks are:

| Unit A | Unit B |
|---|---|
| 1. Coarse-grained, inequigranular | 1. Medium-grained inequigranular |
| 2. Average plagioclase composition of $An_{20}$ | 2. Average plagioclase composition of $An_{10}$ |
| 3. Several types of plagioclase ranging from $An_{30}$ to pure albite | 3. One type of plagioclase |
| 4. Five percent biotite | 4. One percent biotite |
| 5. Accessories in aggregates with biotite | 5. Accessories not with biotite |
| 6. Apatite a common accessory | 6. Apatite rare |

In two separate outcrops, one in Queen Valley and the other in and west of Lost Horse Valley, is an equigranular, fine-grained quartz monzonite (Unit C). Unit C intrudes and sends dikes into the gneiss on the west side of Lost Horse Valley (where the contact is gradational through about an inch), but is clearly older than the White Tank quartz monzonite (as is shown by dikes and other contact features). Although unconnected, the two bodies of Unit C are very similar and almost certainly the same formation; their correlation with Units A and B of the Palms quartz monzonite, however, is based on the following rather tenuous evidence—first, that Unit C grades into Unit B in the eastern part of Queen Valley; and second, that as nearly as can be determined, Unit C is the same age as Units A and B.

Megascopically, Unit C is light brown and generally massive, but some specimens show a faint foliation. Modal analyses of several specimens give the following average results:

| Mineral | Percent |
|---|---|
| Quartz | 30 |
| Potash feldspar | 28 |
| Plagioclase | 38 |
| Biotite | 4 |
| Accessory | 0.2 |

Plagioclase ranges from $An_{10}$ in the eastern part of Queen Valley to $An_{30}$ west of Lost Horse Valley and seems to show a general westerly increase in anorthite content. Quartz and potash feldspar are anhedral, but plagioclase is subhedral. Accessory minerals are uncommon; magnetite is present in most specimens, zircon and apatite are rare, and sphene is absent. Textural characteristics of Unit C which distinguish it from Units A and B are fineness of grain, equigranularity, lack of intergrowths between potash feldspar and plagioclase, and absence of quartzose or biotitic aggregates.

*Structure of the Palms Quartz Monzonite.* Most of the Palms quartz monzonite is either massive or contains local patches of foliated rock which exhibit no general structural trend. Orientation of biotite flakes in portions of Unit B gives the rock a distinct foliation parallel to contacts with the gneissic wall rocks, and thereby, parallel to the foliation in the gneiss.

Jointing is well developed in areas of Palms quartz monzonite which overlie units of the White Tank quartz monzonite. This feature will be discussed in the section on the structure of the White Tank quartz monzonite.

*Contacts Between the Palms Quartz Monzonite and Pinto Gneiss.* Contacts between the Palms quartz monzonite and the Pinto gneiss range from very abrupt to broadly gradational. Most contacts are gradational through a distance from 1 inch to 10 feet, and it is generally possible to distinguish between a poorly foliated, slightly recrystallized and metasomatized gneiss, and the bordering, slightly foliated, quartz monzonite. Only rarely is there a complete mineralogical and textural transition between the two rocks over a distance greater than a few feet. As generally no accessory minerals have been added to the gneiss by the quartz monzonite intrusion, one way to distinguish between the two rocks is by the presence or absence of the accessory minerals. A distinction may also be made on the basis of the detailed textural relations between potash feldspar and plagioclase; but the discussion of both these features is outside the scope of this paper.

*Composition and Texture of the Monzonitic Porphyry.* The typical monzonitic porphyry is brown to gray, coarse grained, and characterized by phenocrysts of potash feldspar which make up 25 to 50 percent of the rock. These phenocrysts are pink to gray, subhedral, and commonly twinned on the Carlsbad law; they have an average length of 15 millimeters, and there is some indication that the crystals in the westernmost of the three principal porphyry bodies are slightly larger than in the other two bodies. Photo 9 shows a single crystal

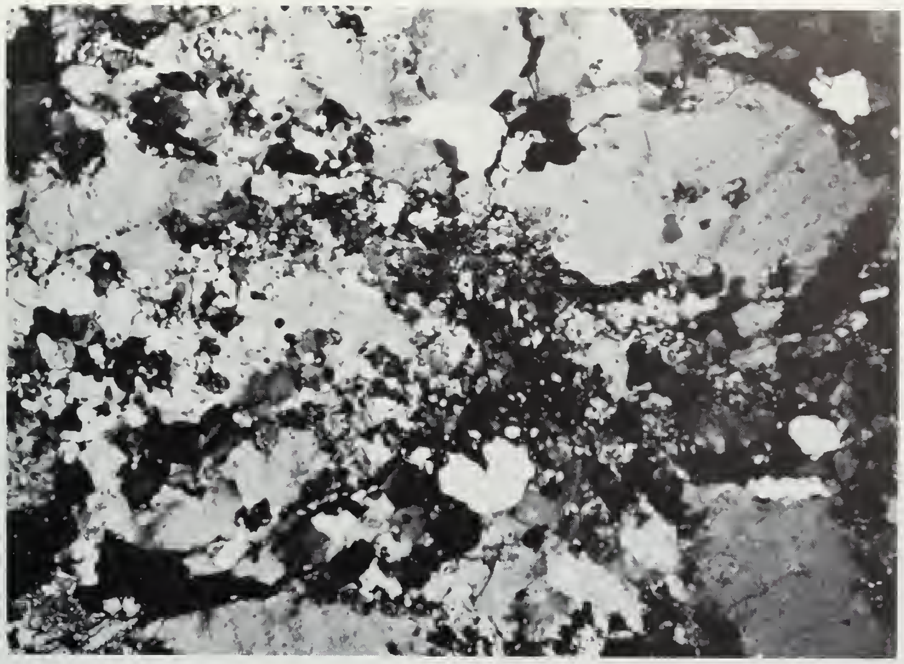


Photo 9. Photomicrograph of monzonitic porphyry. The entire picture represents one large crystol of potash feldspar (the relotively large, gray oreos) in which inclusions moke up 50 percent of the grain. Crossed nicols, X25.

of potash feldspar in which inclusions comprise 50 percent of the grain.

Accurate modal analyses of such coarse-grained rocks as the porphyry are very difficult to make. The composition given below is an estimated average of several analyses and is adjusted to correlate with field measurements of the percentage of potash feldspar.

| Mineral | Percent |
|---|---|
| Quartz | 15 |
| Potash feldspar | 25 |
| Plagioclase | 40 |
| Biotite | 4 |
| Hornblende | 3 |
| Accessory | 2 |
| Groundmass | 10 |

In the porphyry, quartz forms aggregates of anhedral, sutured grains. Potash feldspar, although megascopically appearing as well formed crystals, contains abundant inclusions and has highly irregular borders intergrown with other crystals in the rock. Inclusions may make up to 50 percent of the volume of the potash feldspar crystal, and micrometric measurement shows that the total composition of the inclusions is approximately the composition of the whole rock (the inclusions even consisting partly of small grains of potash feldspar). Plagioclase in the porphyry forms subhedral laths with an average length of 2 to 3 millimeters and a maximum of 10; an average composition is $An_{20}$. Most sections contain hornblende (pleochroic from yellow to blue green). Biotite is pleochroic from yellow to olive green, and in sections of porphyry which contain no hornblende, clusters of biotite and accessory minerals are common. Possibly these clusters formed by alteration of the amphibole. Common accessory minerals are magnetite, apatite, sphene, allanite, and epidote. All of the monzonitic porphyry contains a groundmass of fine-grained quartz and feldspar which makes up 10 to 20 percent of the rock; the average size of most grains in the groundmass is 1/25 millimeter.

*Structure of the Monzonitic Porphyry.* Orientation of potash feldspar grains gives the porphyry a planar structure parallel to some contacts with the gneiss, whether or not these contacts are parallel to the gneissic foliation. Most of the porphyry away from the contacts is massive. Along one contact south of Twentynine Palms the foliation in the porphyry parallels the contact and cuts perpendicularly across the foliation in the adjoining gneiss.

*Contacts Between Monzonitic Porphyry and Wall Rocks.* Most contacts between the Palms quartz monzonite and the monzonitic porphyry are slightly gradational. A few very sharp contacts may be explained as the result of movement of the partially solid porphyry. The principal changes which take place upon passing from the porphyry into the quartz monzonite are: a very large decrease in the size of potash feldspar grains; a slight decrease in the size of plagioclase and quartz grains; possibly a decrease in the percentage of hornblende with respect to biotite; change from greenish to reddish biotite; change from porphyritic texture to an inequigranular seriate one. The porphyry and quartz monzonite are approximately similar in bulk composition, types of accessory minerals, and types of plagioclase.

The contact between porphyry and Pinto gneiss is almost invariably gradational, the transition being far more gradual than the transition between porphyry and quartz monzonite. Changes upon passing from porphyry to gneiss are: a decrease in grain size of all minerals; a decrease in the percentage of potash feldspar; a decrease in the percentage of accessory minerals; a decrease in the albite content of the plagioclase; an increase in the percentage of dark minerals; an increase in the quality of foliation; probably a decrease in the ratio of hornblende to biotite.

*Summary of Relations Between Palms Quartz Monzonite, Monzonitic Porphyry, and Pinto Gneiss.* The principal relations between quartz monzonite, gneiss, and porphyry may be summarized under three headings: distribution, composition, and grain size.

The monzonitic porphyry is roughly peripheral around the northern portion of the Palms quartz monzonite, and in many places the two rocks grade into each other. Unfortunately, the gneiss which probably exists north of the porphyry is not exposed, and it cannot be stated absolutely that the porphyry is a border between gneiss and quartz monzonite. The porphyry is, however, gradational into the gneiss in many places, and local development of the porphyry at the contact between gneiss and quartz monzonite is found in at least two places.

The compositional changes upon passing from gneiss through porphyry into quartz monzonite are: the percentage of quartz decreases from gneiss to porphyry and may increase slightly in the quartz monzonite; the percentage of potash feldspar increases continuously from gneiss through porphyry to quartz monzonite; the percentage of plagioclase increases from gneiss to porphyry and decreases slightly in the quartz monzonite; the total percentage of dark minerals decreases steadily from gneiss through porphyry to quartz monzonite; the percentage of accessory minerals increases from gneiss to porphyry and may decrease slightly in the quartz monzonite; the albite/anorthite ratio for the whole rock (including all the separate phases of plagioclase) increases steadily from gneiss through porphyry to quartz monzonite.

The significant feature concerning grain-size distribution in the gneiss, porphyry, and quartz monzonite is that potash feldspar, plagioclase, and hornblende are all larger in the porphyry than in the other two rocks. The porphyry is also the only one of the three rocks which exhibits a distinct separation between large crystals and a groundmass. The extremely large size of the potash feldspar in the porphyry compared to its size in the quartz monzonite is especially remarkable in view of the fact that the quartz monzonite contains a higher percentage of potash feldspar. Evidently, conditions in the monzonitic porphyry at the time of its formation were favorable to the growth of large grains and were totally different from conditions in either the gneiss or the quartz monzonite.

*Origin of Palms Quartz Monzonite and Monzonitic Porphyry.* The Palms quartz monzonite and the monzonitic porphyry are believed to be related in origin. Their similar mineralogy, the gradation between the two rocks in some places, and the distribution of the porphyry peripheral to the quartz monzonite all indicate a genetic relationship between the two rocks.

This genetic relationship is substantiated by the fact that the porphyry is compositionally intermediate to the gneiss and quartz monzonite, and partly for this reason the writer believes that the monzonitic porphyry formed by reaction between the quartz monzonite melt and the surrounding gneiss. Apparently the intrusive rock supplied potash feldspar and sodic plagioclase ($An_{15}$ to $An_{00}$), or potash and soda, to the gneiss. Other evidence for the transformation of the gneiss to porphyry is in the complete gradation between the two rocks. Sharp contacts between porphyry and both gneiss and quartz monzonite in places indicate that, at least locally, the porphyry was sufficiently mobile to intrude the other rocks. Actually, the planar structure in portions of the porphyry which appear to have undergone movement near some contacts suggests that only a small portion of the porphyry was liquid at the time of movement. Presumably, growth of crystals in the partially solid wall rock around the quartz monzonite led to the formation of some very large grains and a resultant porphyritic texture.

The exact mode of formation of the Palms quartz monzonite is in doubt. It is proposed, however, that the quartz monzonite crystallized from an intruded melt, for, though there is complete gradation between quartz monzonite and both gneiss and porphyry in many places, the transitions are generally complete within a few feet. It appears easier to explain this phenomenon by reaction between a fluid quartz monzonite and a solid wall rock than by replacement in the solid state. Also, dikes of quartz monzonite in both porphyry and gneiss indicate that parts of the quartz monzonite were mobile during at least part of its period of formation. What is more, if the quartz monzonite had formed in the same manner as the porphyry (i.e., by partial incorporation of the surrounding rocks), one would not expect the grain sizes of both potash feldspar and plagioclase to be maximum in the porphyritic rims and smaller in the center of the area of replacement; rather, the grain sizes should increase from the rim toward the center of the quartz monzonite.

It may be that the Palms quartz monzonite is partially the product of injection and crystallization of fluid material and partially the product of solid-state replacement, with the percentage of rock formed by each process unknown.

### White Tank Quartz Monzonite

The White Tank monzonite (White Tank quartz monzonite) was described by Miller (1938). The formation probably represents a Jurassic intrusion.

According to Dr. D. F. Hewett (personal communication), the White Tank quartz monzonite is similar to rocks of apparent Jurassic age elsewhere in the Mojave Desert, and a pegmatite in the Cactus quartz monzonite (a possible correlative) has been dated by Hewett and Glass (1953) as approximately 150 million years old, thus Middle Jurassic.

*Composition and Texture.* The White Tank quartz monzonite is light brown to gray, massive, coarse to medium grained, and inequigranular. Slight textural and compositional differences occur between different intrusive masses and between different parts of the same mass, but individual hand specimens are generally homogeneous. Modal analyses give the following average composition:

| Mineral | Percent |
|---|---|
| Quartz | 30 |
| Potash feldspar | 30 |
| Plagioclase | 35 |
| Biotite | 4 |
| Hornblende | Rare |
| Muscovite | Rare |
| Accessory | 1 |

Photo 10. Photamicrograph of White Tank quartz monzanite. The picture shaws a grain of plagioclase, ane half af which is twinned and the other holf zoned. Crossed nicols, X65.

In the quartz monzonite, quartz is almost invariably in aggregates of undulant, fretted grains. Potash feldspar is generally pink, anhedral, and has an average maximum dimension of 5 millimeters. Plagioclase occurs as subhedral, twinned or zoned laths with an average length of 2 millimeters and an average composition of $An_{20}$. Biotite is pleochroic from yellow to brown and forms very irregular flakes, commonly in clusters with the accessory minerals. A few grains of common blue-green hornblende were found in sections from one part of one intrusive body. Some portions of the quartz monzonite contain apparently primary muscovite in flakes with an average length of 1 millimeter. The common accessory minerals are magnetite, apatite, and sphene. Zircon forms pleochroic halos in some biotite flakes. Allanite is present in a few sections. Manganiferous garnet occurs as small euhedrons in the muscovite-bearing, highly albitic portions of the quartz monzonite.

Myrmekite, rod and vein perthite, and graphic textures are common in the quartz monzonite. Most of the myrmekite is associated with pure albite, which rims the plagioclase laths or forms small, irregular grains inter-

Phato 11. Photomicrogroph of White Tonk quartz monzonite. The picture shows the final product of differentiation in the lorge body sauth af Queen Mountain. Minerals are quartz (undulant), plagioclase (twinned), and microcline (large, grid twinned, groins). Kaolinization of the feldspors is intense. Crossed nicols, X25.

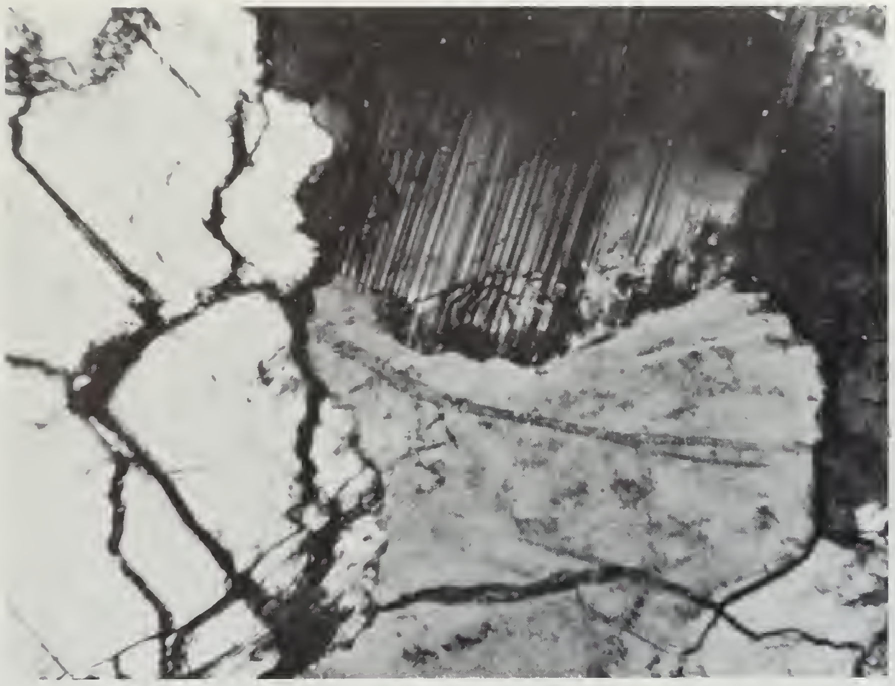


Photo 12. Photomicrograph of White Tank quartz monzonite. Picture shows irregular myrmekite formed in the outer part of a plagioclase grain next to potash feldspar. Crossed nicols, X65.

stitial to the other minerals in the rock. Plagioclase in the rod perthite is commonly of the same composition as the neighboring plagioclase laths and, therefore, has presumably formed by exsolution; plagioclase in the vein perthite may have any composition from the composition of the laths to pure albite. Graphic textures are common only in some border phases of the quartz monzonite or in the outer portions of some large potash feldspar grains.

The irregular, unoriented, intergrowths between potash feldspar and plagioclase so characteristic of the Palms quartz monzonite are not present in the White Tank quartz monzonite. The more acidic portions of the White Tank quartz monzonite do contain oriented intergrowths between sodic oligoclase and microcline, but they are not characteristic of the formation as a whole.

Two distinct trends of differentiation may be identified in the White Tank quartz monzonite. One trend leads to the formation of a rock characterized by abundant, large gray crystals of microcline intergrown with sodic oligoclase. The other trend results in the formation of a highly micaceous, albitic, rock containing small manganiferous garnets.

The first trend is illustrated by vertical differentiation in the large body south of Queen Mountain. In hand specimen the vertical change is best illustrated by the appearance of the potash feldspar crystals; in the lower parts of the rock the feldspar grains are pink, anhedral, and have an average length of 2 to 3 millimeters, whereas in the upper part of the rock the grains are gray, subhedral, and have an average length of 7 to 8 millimeters. The large gray potash feldspar crystals are intergrown with white streaks of sodic oligoclase. Microscopically, it may be seen that the overall composition of the plagioclase changes from sodic andesine at the base to sodic oligoclase at the top. Observable in both hand specimen and thin section is the fact that the biotite decreases in both grain size and percentage from the base to the top of the rock unit; biotite composes about 10 percent of the rock at the base and about 3 percent at the top. Other upward changes in the quartz monzonite include an increase in the amount of vein perthite, an increase in the amount of myrmekite and separate grains of albite, and an increase in the amount of graphic intergrowth. All changes appear perfectly gradational from the base to the top of the body. The rock in the small body east of Queen Mountain apparently represents an intermediate stage of this differentiation sequence; it contains a high concentration of large gray phenocrysts of potash feldspar but has plagioclase grains with a composition of calcic oligoclase.

The second differentiation trend is best illustrated by the formation of a micaceous eastern rim along the upper portions of the eastern contact of the quartz monzonite in Lost Horse Valley; the body of White Tank quartz monzonite between Forty Nine Palms and Queen Mountain appears to represent a continuation of this trend. The rock formed by differentiation in this sequence is characterized by books of primary muscovite up to 10 millimeters long, white, anhedral microcline grains with an average length of 2 millimeters, subhedral plagioclase laths with a composition of $An_{03}$, and small manganiferous garnets. Thus, differentiation has led to a decrease in the size of the microcline grains, an increase in the albite content of the plagioclase, and the formation of two minerals (muscovite and garnet) not common to the main bodies of quartz monzonite.

*Structure.* Almost no megascopic structure, with the exception of the widespread jointing, is to be found in the White Tank quartz monzonite. Most of the rock is massive, and no simple pattern has been discerned from the isolated patches that show a poorly developed foliation. The massive nature of the rock obtains even a few feet from the contacts.

Photo 13. Cap Rock, view east. Note jointing and spheroidal weathering of White Tank quartz monzonite. *Photo courtesy National Park Service.*

Phata 14. Typical bouldery expasure of weathered White Tank quartz monzonite, near Lost Horse Well. *Photo courtesy National Park Service.*

Joints, however, are a characteristic feature of the quartz monzonite (Photos 13, 14). The most commonly developed jointing is a sub-horizontal sheeting which is present at all places in the quartz monzonite. Other joints are most commonly vertical but may have any dip from 45 to 90 degrees. Generally, the joints form a set in which the two major directions of strike intersect at a right angle. They appear to have formed synchronously, as no joint offsets any other.

In Lost Horse Valley and the north part of Queen Valley, joints in the White Tank quartz monzonite have an identical pattern to those in the Palms quartz monzonite. Many individual joints cross the contact with no deflection. Both radial and concentric patterns are present in the quartz monzonite near contacts with the gneiss. The gneiss is generally unjointed even near the quartz monzonite.

*Contacts Between the White Tank Quartz Monzonite and its Wall Rocks.* Contacts between the White Tank quartz monzonite and any of its wall rocks are characterized by their abruptness. Gradation nowhere extends through more than a few inches, and most contacts are knife-edged. The intrusion of the quartz monzonite has had no visible effect on any of the wall rocks except for some slight ingestion of the Gold Park gabbro-diorite.

Near most of its contacts the quartz monzonite exhibits notable textural differences from rock in the center of the large bodies. In many places the grain size of all minerals decreases toward the border; or locally, the grain sizes of quartz and potash feldspar decrease toward the border, and the size of the plagioclase remains constant. Pegmatitic segregations are common a few feet from some contacts. The quartz monzonite at some knife-edged contacts exhibits a partially resorbed quartzose rim with an average width of one inch.

Most contacts of the quartz monzonite are apparently vertical over the small interval observable in the field. The complete three-dimensional configuration of the intrusive masses, however, is unknown.

*Dikes Associated with the White Tank Quartz Monzonite.* In many places the quartz monzonite forms small dikes which cut the surrounding rocks. These dikes are generally characterized by a grain size smaller than that of the associated major intrusive body, and some dikes are porphyritic. The compositional range of the dikes is the same as that of the large bodies of quartz monzonite.

The quartz monzonite is cut by abundant aplite dikes, generally less than one foot wide. These dikes are fine grained, equigranular, and massive. The aplite is generally slightly more silicic than the quartz monzonite which it cuts, but the compositional range of the aplites overlaps the compositional range of the quartz monzonite. The aplite dikes are apparently earlier than the joints which cut the quartz monzonite, for the dikes rarely follow joint planes.

Pegmatite dikes are also earlier than the joints, but wherever the age relations are discernable, the pegmatite postdates the aplite. Most of the large pegmatite dikes are zoned, with potash feldspar (and albite in some cases) near the edge of the dike and quartz in the center. Small dikes are generally unzoned. The composition of individual dikes ranges from nearly pure feldspar to nearly pure quartz.

Rarely, other types of dikes are found cutting the quartz monzonite. The various types noted are a quartz-latite-porphyry, an epidote-albite dike, and a dike consisting of equal amounts of hornblende and andesine.

*Origin.* The White Tank quartz monzonite is believed to have formed by crystallization of an intruded magma, for textural and compositional lack of homogeneity represented by vertical variation in individual bodies and between different bodies of the quartz monzonite is most easily explained by crystallization differentiation of a magma. Rock bodies which have come to equilibrium by solid-state reactions should be far more homogeneous than the White Tank quartz monzonite. In addition, the fine-grained borders and pegmatitic segregations along contacts seem compatible only with formation by cooling of a magma. The very abrupt contacts with no relicts of wall rocks in the quartz monzonite, too, are most easily explained by injection and crystallization of a magma.

*Relations Between the White Tank Quartz Monzonite and the Southern California Batholith.* It might be expected that two large bodies of plutonic rock of approximately the same bulk composition, same age (late Mesozoic), and geographically separated by no more than 100 miles should exhibit roughly the same general features. And as mentioned previously, many quartz monzonitic rocks in the Mojave area are very similar to the White Tank quartz monzonite.

The individual silicic to intermediate plutons of the southern California batholith,* however, differ considerably in some respects from the individual bodies of the White Tank quartz monzonite.† The features characteristic of the White Tank but absent or at least not widespread in the exposed parts of the southern California batholith include the abundant evidence of differentiation (especially gravitative settling) in any one intrusive body; the fine-grained rims and other pronounced textural variations related to contacts (such variations are not common in the southern California batholith); and the almost complete absence of inclusions and evidence of ingestion of wall rocks.

The White Tank quartz monzonite and the rocks of the southern California batholith are similar, however, in the abruptness of almost all contacts with the wall rocks, and in the conformity of foliation in the wall rocks with the outline of the contact.

The reasons for the above-noted differences between the White Tank quartz monzonite and the rocks of the southern California batholith are not known. It is pointless to say that the differences may be caused by a difference in temperature of crystallization of the minerals in the two rocks, for magmas of similar composition should crystallize over the same temperature range unless their environments of formation differ with regard to some other variable, such as pressure. Compositions of the rocks are so similar that any differences must be related to fugitive constituents of the magmas from which the rocks crystallized; but evidence of reac-

* For a detailed description of the northern part of the batholith, see Larsen (1948).

† Several of the distinctions mentioned here were suggested by Dr. R. H. Jahns.

tions involving water in the batholith, and evidence of crystallization from a highly fluid medium in parts of the quartz monzonite indicate that both rocks may well have had about the same concentration of fugitive material. A possible cause for the differences between the White Tank quartz monzonite and the rocks of the southern California batholith is a difference in depth of intrusion below the surface and a consequent difference in pressure on the magmas. Possibly the greater evidence of differentiation in single bodies of the White Tank quartz monzonite than in plutons of the batholith indicates greater depth of intrusion (and consequent slower rate of cooling) for the quartz monzonite. Fine-grained rims in the quartz monzonite bodies and their absence in the batholith suggest lower temperatures in the wall rocks around the quartz monzonite than around the batholith; these higher temperatures possibly resulted from the long sequence of intrusions which characterizes the batholith and which may have warmed the wall rocks in the area.* The White Tank quartz monzonite was not part of such a sequence, and its wall rocks, though deeper than those of the batholith at the time of intrusion, may have been cooler. Mainly by a process of elimination, one reaches the conclusion that the principal difference between the environments of formation of the White Tank quartz monzonite and the southern California batholith was depth of intrusion.

### Granodiorite

The granodiorite, a rock that is possibly related to the White Tank quartz monzonite, crops out in an area south of Jumbo Rocks and north of the Hexie Mountains. Megascopically, it is white to light gray, massive, medium to coarse grained, inequigranular, and locally contains white phenocrysts of plagioclase up to 10 millimeters long.

A modal analysis of the granodiorite gave the following composition:

| Mineral | Percent |
|---|---|
| Quartz | 27.5 |
| Potash feldspar | 11.3 |
| Plagioclase | 48.0 |
| Biotite | 9.4 |
| Hornblende | 2.7 |
| Accessory | 1.0 |

Quartz occurs as aggregates of undulant, fretted, grains or as slightly smaller (0.5 millimeter) interstitial grains. Potash feldspar occurs as anhedral grains with an average size of 0.5 millimeter. Plagioclase forms subhedral laths having an average length of 1.3 millimeter and an average composition of $An_{35}$. Biotite is pleochroic from yellow to dark brown, and hornblende is pleochroic from yellow green to blue green. The accessory minerals are magnetite, apatite, sphene, and zircon. Approximately one-third of the rock can be considered a groundmass of 0.25- to 0.5-millimeter grains of all minerals in the rock.

Compositionally, the granodiorite is very similar to the lowermost part of the neighboring body of White Tank quartz monzonite, but texturally there seems to be little relation between the two rocks. All of the quartz monzonite is coarser grained, has more of its quartz in aggregates, and lacks the distinct groundmass of the granodiorite. The only portion of the White Tank quartz monzonite which is texturally at all similar to the granodiorite is in a relatively fine grained (apparently chilled) zone within one hundred feet of the eastern border of the body south of Queen Mountain; the granodiorite is not related to a border of the quartz monzonite.

Thus, the granodiorite may have been derived from the same magma source as the White Tank quartz monzonite but probably was intruded at a different time. Possibly the granodiorite is a large dike injected soon after crystallization of the quartz monzonite.

### Dikes

Scattered throughout the mountains around Forty Nine Palms are numerous small dikes which are too small to map on the scale used by the writer. They are rarely

* See Larsen (1948), p. 141.

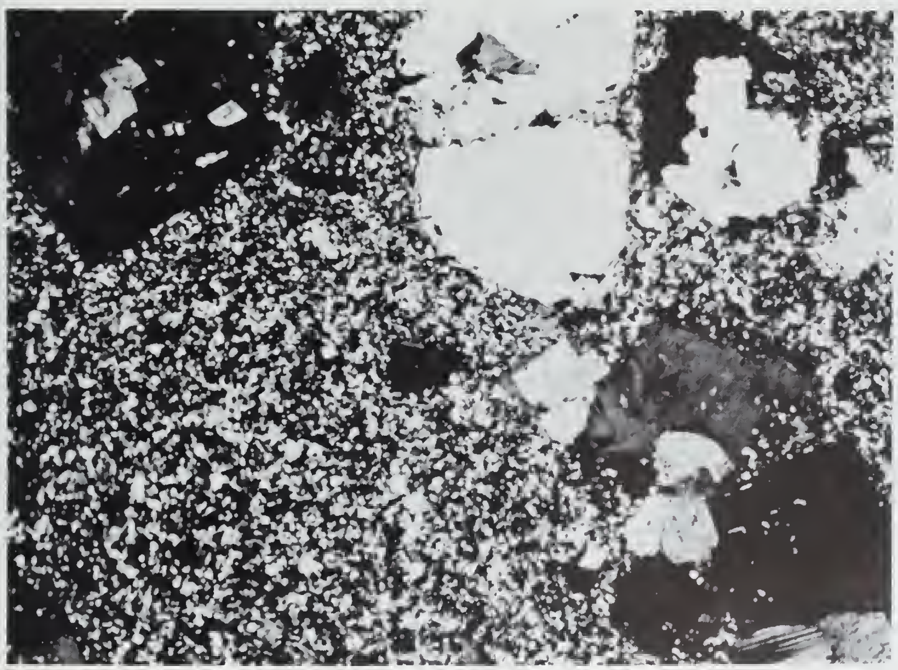


Photo 15. Photomicrograph of silicic dikes. Phenocrysts are quartz (white), plogioclase (groy), ond potash feldspar (block, containing small patches of twinned plagioclase). Groundmass is o mixture of quortz ond feldspar.

Photo 16. Aerial view east across Malapai Hill, a volcanic cone, composed of basalt (dark) cutting White Tank quartz monzonite (bouldery outcrops). West edge of Hexie Mountains in middle distance composed of Pinto gneiss (dark) intruded by White Tank quartz monzonite (light). Squaw Tank and Pleasant Valley just off photo at right. *Photo courtesy National Park Service.*

more than one foot thick and generally can be traced for only a few feet in outcrop. These dikes cut the Palms quartz monzonite and monzonitic porphyry, but their age relation to the White Tank quartz monzonite has not been determined. It has also been impossible to determine whether or not these dikes are related to one of the major plutonic intrusions.

*Composition and Texture.* Two types of dike rock occur: white to light gray, silicic dikes; and, in lesser amounts, greenish-gray, basic dikes.

The silicic dikes (Photo 15) contain about 20 percent phenocrysts, 0.5 to 1 millimeter in diameter, consisting of quartz, potash feldspar, and plagioclase. The potash feldspar phenocrysts are anhedral, may exhibit zones of slightly different crystallographic orientation, and may contain inclusions of quartz in the outer portions of the grains or along the zonal borders. Plagioclase forms subhedral to euhedral, faintly zoned and/or twinned, grains with an average composition of $An_{30}$. Quartz occurs in subhedral, equant grains. The groundmass consists of quartz, potash feldspar, and plagioclase (in that order of abundance). A few biotite flakes, muscovite flakes, and some opaque white powder make up the rest of the groundmass. The average grain size in the groundmass is 0.1 millimeter or less and is different in different dikes or in different layers of the same dike.

The basic dikes contain approximately 30 percent hornblende, pleochroic from yellowish green to greenish blue; 5 percent biotite, pleochroic from yellow to reddish brown; 45 percent irregularly twinned, strongly zoned plagioclase with a compositional range from $An_{50}$ in the center to $An_{30}$ on the edge; 20 percent quartz; and a little magnetite, apatite, and allanite. All grains are anhedral and average 0.1 millimeter in size (except for some plagioclase laths which are seriate from the groundmass size up to 1 millimeter). Some of the quartz occurs in aggregates of 0.5-millimeter grains. Sericitic alteration is abundant in the center of many plagioclase grains.

*Structure.* All of the dikes appear massive both in hand specimen and thin section.

*Origin.* Both the silicic and basic dikes have almost certainly been formed by intrusion and crystallization of a melt. The distinction between phenocrysts and groundmass is partly caused by chilling of a partially crystallized melt, although the inclusions of groundmass in the outer portions of potash-feldspar phenocrysts indicate that at least some of the groundmass started crystallizing before the feldspar phenocrysts stopped growing.

#### Basalt

Malapai Hill (Photo 16), is composed largely of black, aphanitic, olivine-bearing basalt. Similar rock is present at one place (not mapped) along the western part of the Lost Horse Mountains. No flows are associated with the basalt of Malapai Hill, and apparently it is a shallow intrusive rock. Columnar structure is commonly vertical but forms wide loops and is nearly horizontal in places. The basalt cuts the White Tank quartz monzonite and is probably quite young, but its true age is unknown.

### SUMMARY OF STRUCTURAL FEATURES

*Faults.* The area is cut by three major faults, all of which trend east-west and are associated with definite scarps. The absence of faults without associated scarps may simply indicate the difficulty of recognizing faults in crystalline rocks without the aid of related topographic features.

The Pinto Mountain fault, first named by Hill (1928), is apparently the largest fault in the region. It crops out about a quarter of a mile north of the Pinto and part of the Little San Bernardino Mountains and this movement may have been responsible for part of the uplift of these mountains. The Pinto Mountain fault has recently been discussed by Allen (1957).

The Eagle Mountain fault, also named by Hill (1928), marks the southern edge of the Hexie Mountains in Pleasant Valley and cuts through the Little San Bernardino Mountains along two sharp canyons. The movement on the fault is unknown.

The other major fault in the area is a hypothetical one along the south face of Queen Mountain. The sharpness of this face and the difference in rock types north and south of the mountain front indicate the possible presence of a fault. The evidence, however, is not conclusive.

*Joints.* The only rocks in the area in which jointing is well developed are the White Tank quartz monzonite and portions of the Palms quartz monzonite overlying masses of the White Tank. In some places, especially near the axes of minor folds, the gneiss is broken into small, many-sided blocks which certainly represent a type of jointing; but major joint patterns are restricted to the large plutonic bodies. Joints in the White Tank quartz monzonite include a horizontal sheeting and two roughly vertical sets of joints intersecting at nearly right angles. The orientation of these vertical joints varies from place to place, but commonly one joint direction is parallel and one normal to the contact with surrounding gneissic wall rocks. The trend of the vertical joints extends unchanged into thin layers of Palms quartz monzonite overlying the White Tank quartz monzonite, but the joint blocks are generally slightly smaller in the Palms quartz monzonite.

*Foliation.* The only foliated rocks in the area are the Pinto gneiss and Unit B of the Palms quartz monzonite. In general, foliation trends north or northwest where it is not warped into other orientations in the vicinity of the White Tank quartz monzonite. In some places in the western part of the Little San Bernardino Mountains, the foliation in the gneiss strikes nearly east-west, but such places seem to represent merely local flexures in the general northwesterly strike. Foliation in the gneiss is commonly vertical except where the strike differs markedly from the northwest. Foliation in Unit B of the Palms quartz monzonite generally has the same orientation as that in the neighboring gneiss.

### GEOLOGIC HISTORY

The geologic history of Joshua Tree National Monument spans an undetermined length of time and involves a long sequence of intrusions and periods of metamorphism.

Probably the first event which can now be deciphered was the sedimentary and possible volcanic accumulation of material which has since been metamorphosed to form the Pinto gneiss. This gneiss, a formation of great areal extent, forms the terrain into which all of the intrusive

rocks in the area have been injected. Following, or as a late stage of, the metamorphism which formed the typical gneissic rock, was the development of the non-foliated, granitoid, parts of the rock mapped as Pinto gneiss. The granitoid rock does not appear to be related to any of the intrusions in the area.

Age relations of the Gold Park gabbro-diorite are uncertain. The rock appears to intrude the Pinto gneiss, but it may have injected the sediments before their metamorphism to form the gneiss. Relations between the gabbro-diorite and the Palms quartz monzonite are equally uncertain, although in some places the quartz monzonite appears to be the younger rock.

The Palms quartz monzonite is definitely younger than at least most of the rock mapped as gneiss and probably was formed by crystallization of a magmatic intrusion into the gneiss. Along some of the borders between gneiss and quartz monzonite is a small amount of migmatization and injection, and some of the Pinto gneiss may have been derived from igneous material. The major product of the reaction between gneiss and quartz monzonite, however, is the monzonitic porphyry. The porphyry has formed around the northern periphery of Units A and B of the Palms quartz monzonite apparently by reaction between the intrusion and the wall rock.

Following the formation of the porphyry and Palms quartz monzonite was the intrusion and crystallization of the White Tank quartz monzonite, the youngest major plutonic rock in the area. A small mass of granodiorite is probably related to the quartz monzonite but is apparently a somewhat later injection. Joints in the quartz monzonite and some of its wall rocks are evidently later than the crystallization of the quartz monzonite but may be related to late stage cooling stresses in the intrusion.

Numerous small silicic and basic dikes cut the Palms quartz monzonite and monzonitic porphyry and have probably been injected after all of the plutonic activity in the area. Their age relations to the White Tank quartz monzonite and the granodiorite, however, are not certain.

The youngest igneous rock in the area is the olivine basalt which forms Malapai Hill. Apparently it represents a shallow injection for which there may or may not have been extrusive equivalents. The age of the basalt is unknown, but it may be very recent.

The only discernible faulting is younger than all of the igneous rocks in the area with the possible exception of the basalt. Associated and probably synchronous with the faulting are the fans and pediments which have been developed next to the fault scarps.

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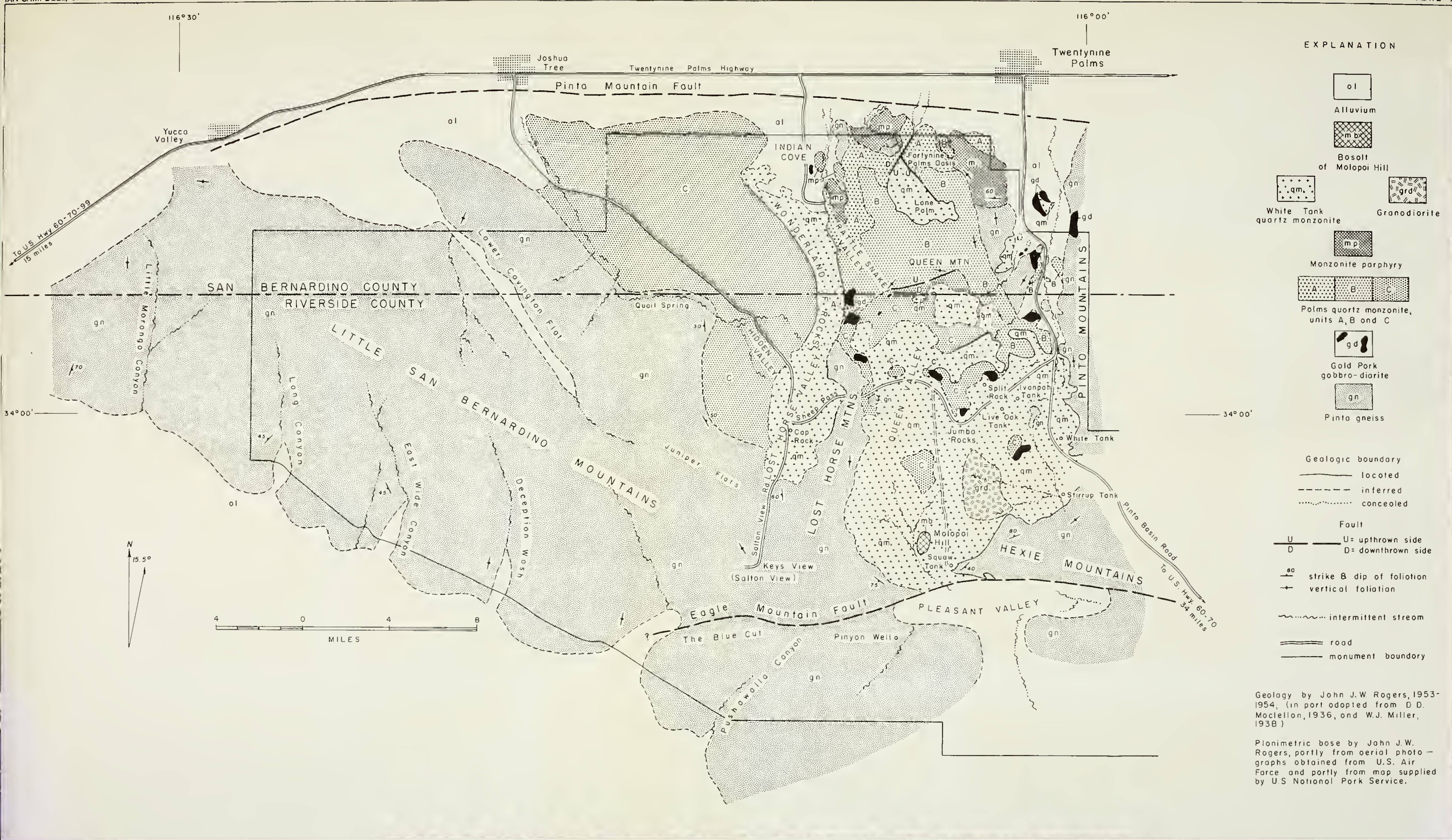
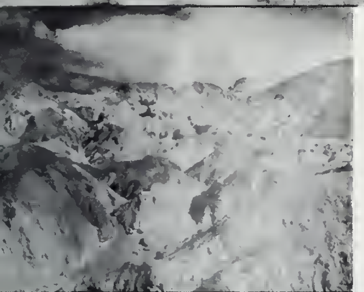



GEOLOGIC MAP OF THE WESTERN PORTION OF JOSHUA TREE NATIONAL MONUMENT
RIVERSIDE AND SAN BERNARDINO COUNTIES, CALIFORNIA



# Clay Minerals

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## California

*Special Report 69*

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